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Estimation of dielectric behaviour of bulk material using its powder

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Abstract : Dielectric parameters of low loss bulk materials are correlated with their powdered form For this purpose, measurements of dielectric constant and loss tangent are carried out on powders of different grain-sizes for three samples namely, two different varieties of marble and one variety of soap stone at 9 921 GHz. Using these values, dielectric constant and loss tangent values are estimated for the bulk material. A comparison of results is done for all the three samples between the calculated values for bulk material and the results obtained from Bottcher's formula.

Keywords : Dielectric constant, loss tangent, bulk material

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Different workers [1,2] have tried to correlate dielectric behaviour of bulk materials and their powders for a long time. Non-availability of required size of bulk materials for mounting in the wave guides some time restricts us to analyse the dielectric behaviour of the material. Bottcher [3] gave a useful relation to correlate dielectric behaviour of bulk material and its powder form.

In recent past, Gandhi and Yadav [4] suggested a simplified method to calculate dielectric constant, loss factor and conductivity values of powder. This method is perhaps very useful in understanding the structural behaviour of particle in an alternating electromagnetic field. Using this method, study of dielectric behaviour of two different qualities of marble, obtained from Makrana in Rajasthan and Ambaji in Gujarat and soap stone obtained from mines in Udaipur, is carried out. In this paper, the dielectric behaviour of low loss bulk materials and their powdered form are correlated when these materials are placed in the high frequency changing electric field.

A rectangular wave guide filled with a dielectric material of complex permittivity ε_p^* is excited in $TE_{m,n}$ mode, the propagation constant γ_d will be given by

$$\gamma_d = j\frac{2\pi}{\lambda_0}\left[\varepsilon_p^* - \left(\frac{\lambda_0}{\lambda_c}\right)^2\right]^{1/2}. \tag{1}$$

On substituting $\varepsilon_p^* = \varepsilon_p' - j\varepsilon_p''$ and seperating real and imaginary parts, values of ε_p' and ε_p'' will be given by

$$\varepsilon' = \left(\frac{\lambda_0}{\lambda_c}\right)^2 + \left(\frac{\lambda_0}{\lambda_d}\right)^2\left[1 - \left(\frac{\alpha_d}{\beta_d}\right)^2\right], \tag{2}$$

$$\varepsilon'' = 2\left(\frac{\lambda_0}{\lambda_d}\right)^2\left(\frac{\alpha_d}{\beta_d}\right). \tag{3}$$

For low loss materials $\left(\frac{\alpha_d}{\beta_d}\right)^2 \langle\langle\ 1$, hence

$$\varepsilon_p' = \left(\frac{\lambda_0}{\lambda_c}\right)^2 + \left(\frac{\lambda_0}{\lambda_d}\right)^2,$$

and

$$\varepsilon_p'' = \frac{1}{\pi}\left(\frac{\lambda_0}{\lambda_d}\right)^2\left(\alpha_d\lambda_d\right). \tag{4}$$

Here λ_0 is the free space wave length, λ_d is the wave length in dielectric and λ_c is the cut-off wave length of the wave guide. α_d is the attenuation introduced per unit length of dielectric material and β_d is the phase shift introduced per unit length of dielectric material.

Using above relations and the simplified method suggested by Gandhi and Yadav [4], ε_p' and ε_p'' values for Macrana marble, Ambaji marble and soap stone are calculated and tabulated in Table 1.

Now for low loss materials, dielectric constant and loss factor for bulk materials can be correleated with their powder form by the relation

$$\varepsilon_s' = \frac{\left(3\delta + 2\varepsilon_p' - 2\right)\varepsilon_p'}{(3\delta - 1)\varepsilon_p' + 1} \tag{5}$$

and

$$\varepsilon_s'' = \frac{2(3\delta - 1)\left[\varepsilon_p''^3 + \varepsilon_p'^2\varepsilon_p''\right] + \varepsilon_p''(3\delta - 2) + 4\varepsilon_p'\varepsilon_p''}{(3\delta - 1)^2\left(\varepsilon_p'^2 + \varepsilon_p''^2\right) + 2\varepsilon_p'(3\delta - 1) + 1}. \tag{6}$$

If we define $\tan\theta_s = \varepsilon_s''/\varepsilon_s'$ and $\tan\theta_p = \varepsilon_p''/\varepsilon_p'$, then

$$\tan\theta_s = \tan\theta_p\left[\frac{2(3\delta - 1)\varepsilon_p'^2 + (3\delta - 2) + 4\varepsilon_p'}{\left\{(3\delta - 1)\varepsilon_p' + 1\right\}\left\{3\delta + 2\varepsilon_p' - 2\right\}}\right]. \tag{7}$$

Table 1. Dielectric parameter of different powders as a function of packing fraction at room temperature.

Sl. No.	Grain size in microns	Packing fraction	Dielectric constant	Dielectric loss	Dielectric parameters: Using Bottcher's relation		Dielectric parameters: Using relations (5) – (6)		$\tan\theta_s \times 10^5$ Using relation (7)
		δ	ε'_p	ε''_p	ε'_s	ε''_s	ε'_s	ε''_s	
				(i) Macrana Marble					
1	850–1180	0.389	3.742	0.003	15.314	0.0213	15.31	0.0218	139
2	186–850	0.403	4.285	0.0045	17.582	0.0301	17.584	0.0307	171
3	150–186	0.407	4.356	0.0065	17.580	0.0422	17.607	0.0425	240
4	75–150	0.442	4.452	0.0092	15.395	0.0462	15.398	0.0467	300
5	0–75	0.453	4.637	0.0144	15.019	0.0676	15.023	0.0671	450
				(ii) Ambaji Marble					
1	850–1180	0.389	3.89	0.003	14.642	0.018	14.644	0.019	123
2	186–850	0.403	4.168	0.0045	16.096	0.028	16.1005	0.032	174
3	150–186	0.407	4.558	0.0064	16.873	0.036	16.876	0.030	215
4	75–150	0.442	4.849	0.0095	16.952	0.049	16.955	0.046	286
5	0–75	0.453	5.21	0.0149	18.409	0.075	18.413	0.078	409
				(iii) Soap Stone					
1	850–1180	0.389	2.676	0.009	5.597	0.029	5.601	0.0293	523
2	186–850	0.403	2.946	0.015	5.958	0.044	5.962	0.0443	742
3	150–186	0.407	3.038	0.0156	5.859	0.042	5.863	0.0427	718
4	75–150	0.442	3.072	0.020	5.609	0.050	5.613	0.059	898
5	0–75	0.453	3.089	0.130	5.507	0.062	5.512	0.065	1135

For solid bulk ($\delta = 1$), hence $\tan\theta_s = \tan\theta_p$. Using these relations, ε_s' and ε_s'' are calculated for the three materials of different grain-sizes. For comparison of results ε_s' and ε_s'' values are also calculated from Bottcher's relation.

For powders, Bottcher's formula is given by

$$\frac{\varepsilon_p^* - 1}{3\varepsilon_p^*} = \frac{\delta(\varepsilon_s' - 1)}{\varepsilon_s^* + 2\varepsilon_p^*}, \tag{8}$$

where ε_s^* and ε_p^* are complex permittivity of bulk and powdered materials respectively.

These values are presented in the tabulated form in Table 1. Values of $\tan\theta_s$ for three materials of different grain-sizes are also calculated and tabulated in Table 1. It is found that the deviation in $\tan\theta_s$ values obtained from Bottcher's relation and present calculations is almost negligible.

Table 1 lists the values of permittivity ε' and loss factor ε'' with the values of packing fraction δ and the grain-size for the three samples namely, Macrana marble, Ambaji marble and soap stone. These results are tabulated both for powder form and bulk materials. Permittivity ε_s' and loss factor ε_s'' for bulk material, given in the Table 1 are obtained using eqs. 5 and 6. These parameters are also calculated using eq. 8 for comparison of results. It is found that variation of ε_s' and ε_s'' values from both the relations is similar. It can be observed that ε_s' value initially increase and then decreases on increasing packing fraction values for all the three materials. ε_p' values do not depend simply on the particles contributing towards polarisation but also on other local conditions like grain boundaries, their contours and presence of small possible air packets. These are possibly responsible for non-linear variation of ε_s' with packing fraction. On the other hand, ε_s'' values increase with the increase in packing fraction, because ε_p'' values depend directly on the number of dipoles participating the loss. Therefore, ε_p'' values hence ε_s'' values vary linearly with packing fraction.

Validity of these relations (5)–(7) can also be understood from the fact that deviation in ε_s', ε_s'' and $\tan\theta_s$ values obtained from two sets of relations (5)–(7) and (8) is not significantly large. These relations are simple to apply. Hence, estimation of dielectric behaviour of bulk material can be made easily by studying dielectric parameters of its powder.

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